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EXPERIMENTAL SALT WEATHERING OF LIMESTONES IN RELATION TO ROCK PROPERTIES

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ABSTRACT

A total of 21 different types of British and European Mesozoic limestones have been subjected to simulated salt weathering using sodium sulphate (Na_2SO_4) with the following aims: assessment of the relative durabilities of different types of limestone; assessment of the importance of modulus of elasticity and other factors in affecting durability; and assessment of the use of impulse excitation techniques to monitor changes in rock modulus of elasticity. The rocks showed a wide spectrum of durabilities; while rocks with high values of modulus of elasticity, lower water absorption capacities, high densities and low salt uptakes tended to be durable, there were anomalies, the explanation for which probably lies in their pore structures. Non-destructive testing techniques showed that, although the more durable rocks failed to lose weight or to show visual signs of disintegration, their modulus of elasticity values did tend to decline, indicating a loss in strength. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: salt weathering; modulus of elasticity; acoustic techniques; limestone

INTRODUCTION

The purpose of this paper is to describe some experimental laboratory simulations of salt weathering for a range of different limestones, with three aims in mind:

(1) to assess the relative durability of different types of limestone in the face of salt weathering attack;
(2) to assess the importance of modulus of elasticity and other factors in affecting (and predicting) rock resistance to salt weathering;
(3) to assess the use of impulse excitation techniques to measure change of rock strength (as represented by modulus of elasticity) in the absence of obvious visual signs of weathering or of weight loss.

Limestone is a widespread rock type, covering about 11 per cent of the Earth's surface, and salt weathering is an important process in desert, urban, coastal and polar regions (Goudie and Viles, 1997). This paper therefore looks at two central issues in geomorphology: force, as represented by salt weathering; and resistance, as represented by limestone rock properties.

THE ROCKS TESTED

A total of 21 different specimens of Mesozoic limestones from Britain, France and Portugal were employed in this experiment. All samples were cut from quarried blocks and, with the exception of the Cretaceous Chalk from England, all rock types are widely used as building stones. The rocks display a wide range of densities (1·82 to 2·67 g cm^{-3}), water absorption capacities (0·75 to 19·28 per cent) and moduli of elasticity (4·91 to 37·17 Gpa). It might therefore be expected that they would display a wide range of responses to simulated weathering.

The characteristics of the 21 rock types are listed in Table I.

The shape of the samples was kept regular and broadly comparable, with dimensions being 10 × 3 × 2 cm.

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Table I. Characteristics of the 21 rock types

Rock name	Abbreviation	Water absorption capacity (%)	Density (Mg m^{-3})	Modulus of elasticity (GPa)	Comments
Bath Stoke Ground Base Bed	BSG	6·23	2·18	12·85	Oolitic limestone from the Great Oolite (Middle Jurassic), Wiltshire, England
Bath Stone Monks Park	MP	10·56	1·98	9·32	Oolitic limestone from the Great Oolite (Middle Jurassic), Wiltshire, England
Guiting Stone	G	10·08	2·02	7·70	Oolitic limestone from the Inferior Oolite (Middle Jurassic), Gloucestershire, England
Portland Whitbed	PW	7·75	2·11	14·27	Fine-grained limestone with shell fragments, and pelletal material, from Portland Beds (Late Jurassic), Dorset, England
Portland Whitbed	2 PW	4·59	2·36	19·93	Fine-grained limestone with shell fragments, and pelletal material, from Portland Beds (Late Jurassic), Dorset, England
Bath Stone Westwood Ground	WWB	10·24	2·06	11·11	Oolitic limestone from the Great Oolite (Middle Jurassic), Wiltshire, England
Purbeck 'Marble'	PB	0·75	2·67	37·17	A hard, shelly limestone from the Purbeck beds of the Late Jurassic, Dorset, England
Mocha Cream	MC	2·35	2·47	23·12	A coarse-grained Portuguese stone with shell fragments from the Upper Jurassic near Fatima
Clipsham (bluehearted)	CL	2·50	2·50	32·86	Medium-grained Oolitic limestone with shell fragments from the Lincolnshire formation, Middle Jurassic, Leicestershire, England
Ketton	K	7·90	1·93	8·43	Oolitic limestone from the Lincolnshire Limestone, Middle Jurassic, Lincolnshire, England
Chalk	C	19·28	1·82	6·32	A soft Cretaceous limestone from the Upper Chalk, Oxfordshire, England
Richemont	R	11·94	1·99	9·08	A fine-grained Jurassic limestone
Portland Roach	PR	3·59	2·47	26·80	Shelly limestone from the Portland Beds of Late Jurassic age, Dorset, England
Euville	EAU	4·26	2·39	9·72	A large-pored, crinoidal limestone from the Rauracien (Upper Jurassic) from Meuse Department, France
Ancaster Weather Bed	AW	3·25	2·50	27·47	Middle Jurassic oolitic limestone from Lincolnshire, England
Portland Best Bed	PT	6·42	2·22	18·01	Oolitic limestone, fine-grained from Portland Beds (Late Jurassic), Dorset, England
Anstrude	A	6·96	2·24	16·82	An oolitic limestone containing crinoidal debris from the Bathonian of the Lower Jurassic from the Yonne Department, France
Bath Stone Stoke Top Bed	STB	13·41	1·90	4·91	Oolitic limestone from the Great Oolite (Middle Jurassic), Wiltshire, England
Savonnières	S	9·96	1·84	11·12	An oolitic limestone of even texture from the Portlandien (Upper Jurassic) from Meuse Department, France
Bath Stone Stoke Ground Base Bed	SGBB	6·89	2·19	11·79	Oolitic limestone from the Great Oolite (Middle Jurassic), Wiltshire, England
Portland Base Bed	PBB	6·22	2·20	16·29	Oolitic limestone, finegrained, from Portland Beds (Late Jurassic), Dorset, England

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ROCK PROPERTIES

As described in the testing procedure (see below), a range of rock properties has been determined for each cycle. These include: (i) water absorption capacity (WAC), which gives a measure of the amount of water-accessible (as opposed to gas-accessible) pore space; (ii) the amount of salt that the rocks soak up from solution; (iii) density; and (iv) modulus of elasticity. Determination of the modulus of elasticity of the rocks was undertaken using an impulse excitation technique, following Allison (1987).

The modulus of elasticity (or Young's modulus) expresses rock stiffness, as it measures the stress required on an elastic material to produce a specific deformation. It has been used by a variety of workers over many years as a measure of rock or concrete response to weathering processes, including frost (Whalley and McGreevy, 1992; Fahey and Gowan, 1979; Prick, 1997; Stark 1997; Auberg and Setzer 1997), salt weathering (Weiss, 1992; Prick, 1996) and fire (Goudie *et al.*, 1992; Allison and Goudie, 1994). There is a range of reasons for this choice. First, as the elastic behaviour of a rock changes, so does its durability. Secondly, changes in elasticity are caused by a whole range of rock properties (texture, density, porosity, etc.) and can be used as an aggregate index of such properties. Thirdly, there is a close relationship between modulus of elasticity and compressive strength (Allison, 1987) and this is, for example, the case for limestones (Sachpazis, 1990). Fourthly, higher elasticity values indicate less weathered, more competent materials, while lower elasticity values indicate more highly weathered materials. Fifthly, the modulus of elasticity can be measured very simply and non-destructively using ultrasonic techniques. This makes it possible to repeat laboratory simulations on the same specimens, eliminating between-sample variability.

THE TESTING PROCEDURE

The testing procedure was simple and involved the following steps.

1. Three samples of each of the 21 rock types were dried to constant weight in an environmental cabinet at 40°C and 50 per cent relative humidity (RH).
2. They were then weighed to two decimal places and their dimensions were recorded to the nearest millimetre.
3. They were then soaked in distilled water for 48 hours, weighed moist, and then their weights were compared to their dry weights to obtain their water absorption capacities (WAC).
4. They were then dried to constant weight at 40°C and 50 per cent RH and Grindosonic readings were taken. Knowing their weight and dimensions, their densities were also calculated.
5. They were then immersed in a saturated solution of sodium sulphate (Na_2SO_4) for 24 hours, removed from the solution and then dried at 40°C and 50 per cent RH. The difference in weight between this value and their initial dry weight gives a measure of their initial salt uptake.
6. This procedure was continued for another nine cycles, with Grindosonic readings being taken for each sample for which dimensions remained constant.

This procedure was adopted in this simulation rather than a more realistic cycle of the type used elsewhere (e.g. Goudie and Viles, 1995) because it was felt that this would make sure that all rock types underwent some degree of weathering in a finite period of time. Likewise, sodium sulphate was used because of its proven efficacy in comparison with other commonly existing salts.

IMPULSE EXCITATION TECHNIQUE

The impulse excitation technique obtains its information from the analysis of the transient vibration of a test object following a mechanical impact. The energy thus acquired by the tested sample is dissipated in a vibratory movement, the nature of which is dependent on the geometry of the object and the density and elastic properties of the material. The Grindosonic instrument (a non-destructive technique) is designed to

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Table II. Ranking of weathering of the 21 rock types

Rock type	Cycle 1	2	3	4	5	6	7	8	9	10
BSG	10	12	7	8	7	9	10	10	11	11
MP	2	8	9	9	9	8	8	8	8	9
G	7	5	6	6	6	6	7	7	6	6
PW	12	18	12	12	13	14	12	14	15	15
A	3	17	13	11	12	11	11	12	13	13
STB	5	1=	1=	1=	1=	1=	1=	1=	1=	1=
S	8	21	11	7	8	10	9	9	10	10
SGBB	13=	4	5	5	5	5	5	5	5	5
PBB	16	16	17	17	17	17	17	17	17	17
R	6	20	3	3	3	3	3	3	3	3
PR	13=	11	10	13	11	7	6	6	7	7
EAU	19	13	20	20	20	20	20	20	20	20
AW	9	6	19	19	19	19	19	19	18	18
PT	15	15	16	15	15	15	15	16	16	16
WWB	3=	3	4	4	4	4	4	4	4	4
PB	21	7	15	18	18	18	18	18	21	21
MC	18	9	14	16	16	16	16	15	9	8
CL	20	10	18	14	14	13	14	13	12	12
K	11	19	8	10	10	12	13	11	14	14
C	1	1=	1=	1=	1=	1=	1=	1=	1=	1=
2PW	17	14	21	21	21	21	21	21	19	19

These are the mean values of three samples of each rock type.

capture this mechanical vibration, analyse it, and give an accurate measure of the natural frequency; full details are provided by Allison 1998 and Prick 1997.

In this experiment tests were conducted with rock blocks that had been cut to a regular rectangular shape with a diamond bladed saw. The samples all had length to thickness and length to width ratios that were greater than three, for beyond these limits the calculations are less accurate and less reproducible (Allison, 1987, p.64).

To provide a reading on the Grindosonic, each test piece was struck in the centre of its upper face using a glass rod, and a piezo-electric detector (which converts the vibration pattern into an electronic signal) was held in contact with it at the centre of one of the side faces. The tests were conducted with samples resting on a foam mat to damp spurious harmonics. Sample length, width, thickness and mass were carefully determined and with the Grindosonic reading can be used to determine sample density (in Mg m^{-3}) and the modulus of elasticity (in GPa).

METHOD OF DETERMINING RANKING OF WEATHERING

As the experiment progressed, the weights of all fragments greater that 10 g in mass were recorded and were summed to gain an average weight of the three blocks of each rock type. The number of fragments heavier than 10 g was also recorded. The average weight was then determined for each cycle as a percentage of the sample's original dry weight. The average percentage weight loss was the prime determinant of where a rock type was placed in the weathering ranking. For those samples that broke down so that there were no fragments greater than 10 g in mass, the ranking was based on the cycle during which that point was attained. For those samples where, even after 10 cycles, there had been a gain in weight, the ranking was based on visual evidence of weathering, including the development of splits.

After about the fourth cycle there was relatively little variation in the relative rankings of the 21 rock types (Table II) and so it is the relative ranking after Cycle 10 that is used in correlations with rock properties. The only exception to this tendency is the way that the Mocha Cream blocks disintegrated rapidly after Cycle 8.

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TEN CYCLES OF BREAKDOWN

As expected from the wide range of properties displayed by the 21 types of limestone, their responses to simulated weathering were diverse. Their temporal patterning of weight change is shown in Figure 1.

All rocks showed a gain in weight after the first cycle of salt immersion. This was due to salt absorption. Thereafter, they showed three main patterns of behaviour. One group of samples (STB, C, R, WWB, SGBB, G, PR) rapidly disintegrated and so by Cycle 2, two rocks (STB and C) had broken down so that no fragments greater than 10 g in mass remained. Others had behaved similarly by the completion of Cycle 10 (R, WWB, SGBB, G, PR). Another group of samples, eight in number, while never reaching such extreme levels of breakdown, nonetheless suffered substantial weight loss, although initially they may have absorbed substantial amounts of salt, gaining weight at Cycle 2. A third group of rocks showed no weight loss over the 10 cycles, though even some of this group displayed splitting (e.g. AW, 2PW). It was in this third group that the Grindosonic device did indicate some loss of strength even in the absence of weight loss or obvious visual signs of weathering.

THE USE OF GRINDOSONIC EMISSION TECHNIQUES TO DETECT WEATHERING

The Grindosonic technique requires the use of samples of known geometry and so cannot be used to detect strength changes in samples that show obvious visual signs of weathering involving any departure from their original carefully cut shape. However, for samples which show no such changes in geometry, it may be possible for the technique to reveal that changes in rock strength have taken place, notwithstanding the fact that no weight loss occurred.

Table III shows the difference in modulus of elasticity values for five rock types between their initial dry values and their values after 10 cycles of weathering. They all demonstrate a reduction in their values, with the range being between 12·82 and 30·08 per cent.

THE RELATIONSHIPS BETWEEN ROCK PROPERTIES AND ROCK BREAKDOWN

Table IV shows the Spearman rank correlation coefficients between individual rock properties (modulus of elasticity, water absorption capacity, density, and percentage salt uptake) and the degree of weathering after 10 cycles. Table V shows the basic data upon which these correlations are based for the 21 rock types.

As one would expect, because of the basis on which the method is founded, there are very strong correlations ($Rs = 0{\cdot}88$) between modulus of elasticity, rock density and water absorption capacity, and between water absorption capacity and density ($Rs = 0{\cdot}93$). However, the correlations between degree of weathering and the rock properties are rather less strong, and as McGreevy (1996) also found there are many anomalies. The correlations range between 0·59 and 0·64. Thus while there is a general tendency for rocks with high modulus of elasticity values, high densities, low water absorption capacities and low salt uptakes to be resistant to weathering (e.g. PB, 2PW, PBB, AW) and for rocks with low modulus of elasticity values, low densities, high water absorption capacities and high salt uptakes to be susceptible to weathering (e.g. C, STB, R, WWB), there are some rocks which appear to behave anomalously (Figure 2). Notable here are five rocks that show a poor correlation between their modulus of elasticity, WAC and density values and their weathering performance: PR, CL and MC, which weather badly in spite of high modulus of elasticity values, high density and low water absorption capacities; K, which is more resistant than might be predicted; and EAU, which has a high resistance but a low modulus of elasticity.

The three rocks that weather anomalously quickly have one feature in common that may contribute to this phenomenon. They are the three shelliest limestones of the group. The shell material itself may be relatively dense and has a small water absorption capacity, thus giving these characteristics to the bulk sample. Their matrix, on the other hand, may be relatively unresistant and may be their Achilles heel.

Of the two rocks that seem to weather less than might be expected, the explanation for Euville's behaviour may be its pore size characteristics. It possesses exceptionally large pores, and this may limit the pressures that salt build-up can exert, but in terms of its WAC, density and salt uptake it does not behave anomalously.

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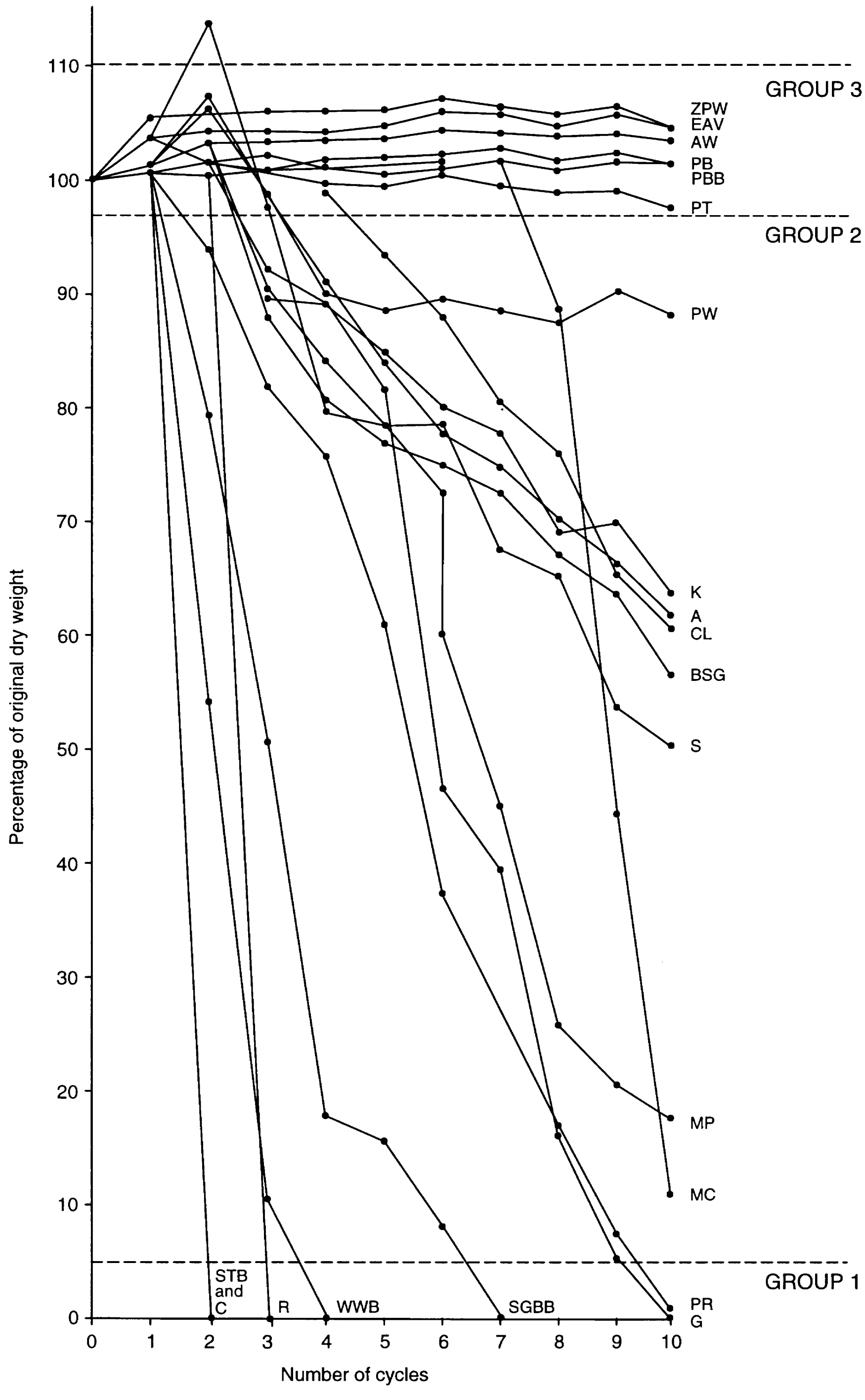

Figure 1. The temporal pattern of weight change of the 21 rock types over 10 cycles. Abbreviations of rock types are listed in Table I

Table III. Modulus of elasticity values for five rock types

Rock type	Initial dry value (GPa)	Value after 10 cycles (GPa)	Value at cycle 10 (% of initial value)
PBB	16·29	11·39	69·92
AW	26·23	22·40	89·35
PT	18·01	14·20	78·84
PB	37·17	29·70	79·90
2PW	19·43	16·94	87·18

Table IV. Correlation matrix of rock properties and weathering response

Modulus of elasticity	–				
Water absorption capacity	0·88	–			
Density	0·88	0·93	–		
Salt uptake (%)	0·65	0·74	0·74	–	
Weathering rank after Cycle 10	0·59	0·67	0·62	0·64	–
	Modulus of elasticity	Water absorption capacity	Density	Salt uptake (%)	Weathering rank after Cycle 10

All correlations are Spearman rank correlation coefficients

Table V. Rock properties and rock breakdown

	Dry strength (GPa)	Rank	WAC (%)	Rank	Density (Mg m^3)	Rank	Salt uptake	Rank	Wet strength (GPa)	Rank	Weathering rank after Cycle 10
BSG	12·85	11	6·23	13	2·18	10	1·43	10	10·33	9	11
MP	9·32	6	10·56	4	1·98	5	3·72	2	7·51	7	9
G	7·70	3	10·09	6	2·02	7	1·70	7	6·42	5	6
PW	14·27	12	7·75	9	2·11	9	1·21	12	13·33	10	15
A	16·82	14	6·96	10	2·24	14	2·80	3=	16·07	12	13
STB	4·91	1	13·41	2	1·90	3	2·22	5	3·99	1	1=
S	11·12	9	9·96	7	1·84	2	1·53	8	9·75	8	10
SGBB	11·79	10	6·89	11	2·19	11	1·17	13=	-	-	5
PBB	16·29	13	6·22	14	2·20	13	1·04	16	14·89	11	17
R	9·08	5	11·94	3	1·99	6	2·13	6	6·08	4	3
PR	26·80	18	3·59	17	2·47	17=	1·17	13=	24·04	16	17
EAU	9·72	7	4·26	16	2·39	16	0·72	19	-	-	20
AW	22·47	19	3·25	18	2·50	19=	1·48	9	26·45	17	18
PT	18·01	15	6·42	12	2·22	13	1·15	15	17·56	13	16
WWB	11·11	8	10·24	5	2·06	8	2·80	3=	6·93	6	4
PB	37·17	21	0·75	21	2·67	21	0·22	21	32·54	19	21
MC	23·12	17	2·35	21	2·47	17=	0·95	18	21·71	15	8
CL	32·86	20	2·50	19	2·50	19=	0·66	20	30·62	18	12
K	8·43	4	7·90	8	1·93	4	1·32	11	5·68	3	14
C	6·32	2	19·28	1	1·82	1	5·57	1	4·53	2	1=
2PW	19·93	16	4·59	15	2·36	15	0·98	17	19·36	14	19

These values are the means for three samples of each rock type.

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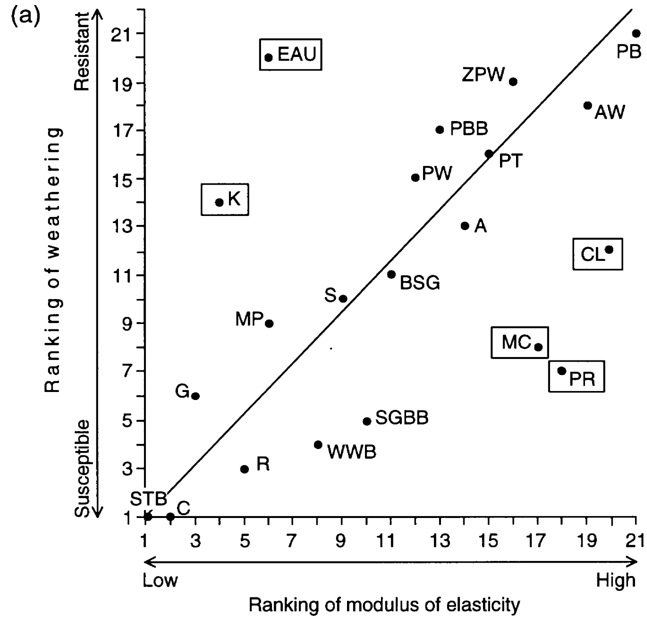

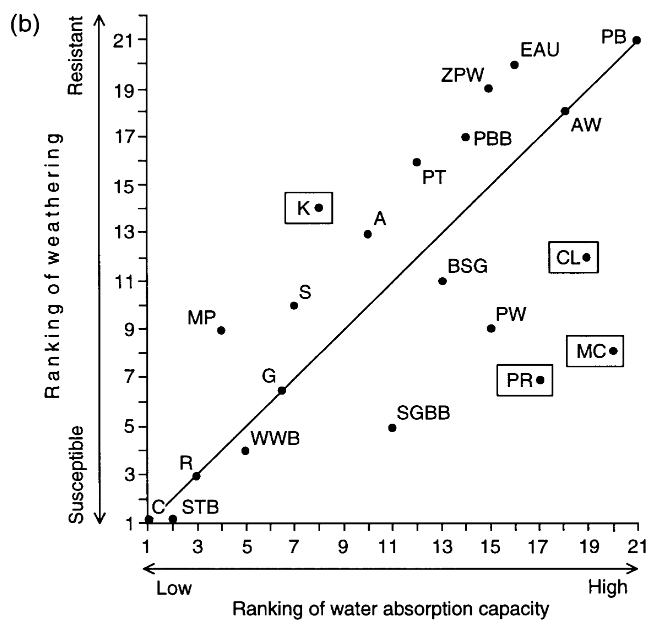

Figure 2. The ranking of rate of weathering against: (a) modulus of elasticity; (b) water absorption capacity. The main anomalies are enclosed in boxes

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It is only its modulus of elasticity value that appears to be exceptionally low in relation to its other properties. The explanation for Ketton Stone's relative resistance may lie in its relatively low saturation coefficient (0·64–0·67) in comparison with most of the rocks tested (Leary, 1983, p. 42). The saturation coefficient is the ratio of the volume of water absorbed to total volume of voids in a material. Rocks which have quite high water absorption capacities may be resistant if their saturation coefficients are low. The microporosity of Ketton Stone is also relatively low (averaging 41·6 per cent), this being defined as 'the volume of water retained (expressed as a percentage of the total available pore space) when a "suction" (negative pressure) equivalent to 640 cm head of water is applied to the test piece of stone' (Building Research Station, 1963). The combination of these two properties probably explains Ketton Stone's superior resistance. However, more work is required using techniques such as Mercury porosimetry to understand the precise role of pore size distributions and pore interconnectedness (Wardlaw *et al*.,1988).

CONCLUSIONS

After 10 cycles of simulated salt weathering with saturated sodium sulphate solutions, the 21 limestone types demonstrated a wide diversity of response in terms of their disintegration. One group of samples broke down rapidly and extensively into fine debris, another group absorbed a large amount of salt but then broke down, and a third group of samples absorbed a limited amount of salt and showed no weight loss and no obvious signs of disintegration. The use of the Grindosonic showed, however, that this resistant group did undergo a decline in modulus of elasticity values.

Although rocks with high modulus of elasticity values, high densities, low water absorption capacities and low salt uptakes tended to be resistant, while rocks with low modulus of elasticity values, low densities, high water absorption capacities and high salt uptakes tended to be susceptible, it is plain that these factors are not in themselves sufficient to explain or predict rock response to salt weathering. Other factors are also probably important, including shell content and pore characteristics (as represented by saturation coefficients and microporosity).

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